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# Laboratory Velocity Measurements Used for Recovering Soil Distributions from Field Seismic Data

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# LABORATORY VELOCITY MEASUREMENTS USED FOR RECOVERING SOIL DISTRIBUTIONS FROM FIELD SEISMIC DATA

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## Abstract

Recent advances in field methods make it possible to obtain high quality compressional (P) and shear (S) velocity data for the shallow subsurface. Environmental and engineering problems require new methods for interpreting the velocity data in terms of sub-surface soil distribution. Recent advances in laboratory measurement techniques have provided high quality velocity data for soils at low pressures that can be used to improve interpretation of field data. We show how laboratory data can be used to infer lithology from field data. We use laboratory ultrasonic velocity measurements from artificial soils made by combining various amounts of sand and peat moss.

## Introduction

This work is part of an on-going environmental geophysics project with the goal of improving underground imaging in the shallow subsurface by developing algorithms relating measured geophysical properties to lithology, porosity, and fluid-flow properties for unconsolidated materials at pressures appropriate for the top 10 m of the subsurface (Berge et al., 1998).

Physical properties measurements made under controlled conditions are critical for interpreting field data in engineering and environmental studies. Recent advances in high-resolution seismic field methods (e.g., Carr et al., 1998; Steeples et al., 1998) and laboratory measurements of ultrasonic velocities at low pressures in unconsolidated materials (Bonner et al., 1997, 1999; Trombino, 1998) provide incentive and data needed to improve seismic imaging of the shallow subsurface.

We developed an inversion code to obtain the soil distribution in the shallow sub-surface from Vp and Vs data. The code minimizes the misfit between the observed Vp, Vs pairs of data in the region of interest and sets of soil velocities measured in the laboratory. The soil distribution is determined by empirical correlation between lithology and velocities that is based on recent laboratory ultrasonic measurements for soils (Trombino, 1998; Berge et al., 1999; Bonner et al., 1999). Our intention was to demonstrate how the addition of the S velocity will constrain the inversion in realistic models when used in conjunction with the P velocity.

In this paper, we show for several realistic models that by using Vp, Vs sets of data we are able to get a better mapping of the subsurface than the one obtained using Vp only. The ambiguity of the reconstruction is reduced by adding Vs data that further constrain the solution space, obtaining better imaging of the soil distribution. In cases where the laboratory data were sparse we were unable to recover the true soil distribution. Here, we first describe the laboratory data we used and the realistic field models of sand-peat soils. We next describe how we simulated field data using the laboratory measurements. Then we discuss the results of our reconstruction of the sand-peat distributions for two models, and make conclusions.

## Laboratory Measurements of Soil Velocities

We used laboratory measurements of soil velocities at low pressures to develop relationships between soil velocities and soil composition. These were ultrasonic velocity measurements of compressional and shear wave velocities for sand-peat mixtures at low pressures (Trombino, 1998; Berge et al., 1999; Bonner et al., 1999). Although other laboratory data sets are available in the exploration geophysics, marine geophysics, and soil mechanics literature (e.g., Rao, 1966; Domaschuk and Wade, 1969; Domenico, 1976; Hamilton and Bachman, 1982), few studies include both compressional and shear velocity measurements as a function of pressure at the extremely low pressures representing the shallow subsurface. The laboratory measurements described in Trombino (1998) were made at pressures between 0 and about 16 psi (about 0.1 MPa) in pressure increments of 1.5 psi, and represent the top few meters of the subsurface. Both compressional and shear velocities were measured for a set of samples containing various proportions of Ottawa sand and commercially available peat moss (Trombino, 1998). Such samples may be representative of shallow soils having a high organic content. Sample construction and laboratory measurement techniques are described in detail in Trombino (1998) and will not be repeated here. Resulting velocities determined from the measurements are described in detail in Berge et al. (1999) and Bonner et al. (1999).

For the purposes of this work, we used the laboratory data to build realistic field models simulating sites having sandy peat soils. Future work will include use of actual field data.

The realistic field models of sand-peat soils used in this paper are based on actual field sites at Mercer Slough near Bellevue, WA (McGuire et al., 1998), and Sherman Island in the Sacramento-San Joaquin Delta in northern CA (Boulanger et al., 1998). These models use simplified versions of the structure and soil distributions that may be found at these field sites. Both realistic field models are simulated using 10x10 grids having cells that are each 1.5 m in the vertical direction and 5 m in the horizontal direction, and four different types of soils. The soils are pure sand; 12% peat, 88% sand by volume; 20% peat, 80% sand; and 70% peat, 30% sand. (See Figures 1a and b.)

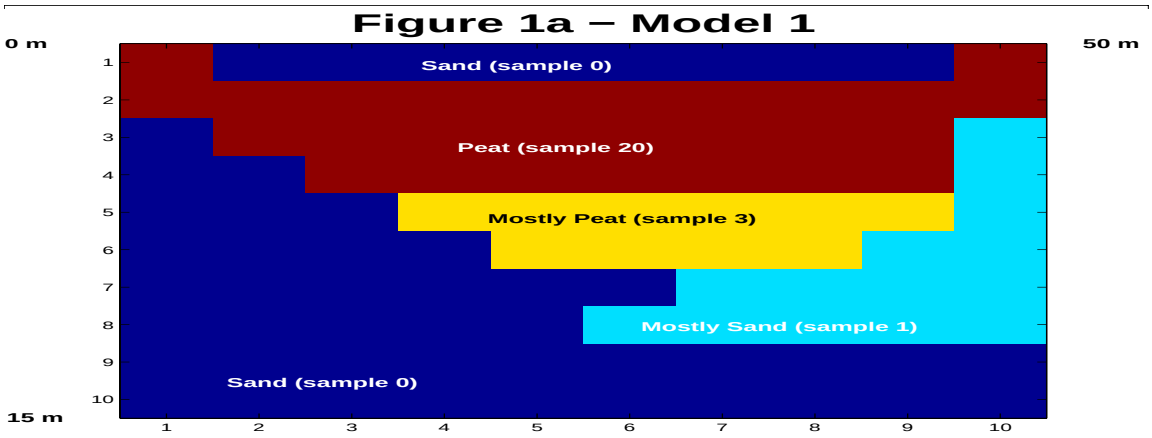


Figure 1a – Realistic Field Model 1 of Sand-Peat Soil Distributions.

Figure 1a shows the Model 1 area of study. This synthetic model is based on an actual field site at Mercer Slough near Bellevue, WA (McGuire et al., 1998). The synthetic models in Figures 1a and 1b are 15 m deep and 50 m long. Black regions indicate pure sand; the blue region indicates a mixture of about 12% peat, 88% sand; the yellow region represents a mixture of about 20% peat, 80% sand; and the brown region represents a mixture of about 70% peat, 30% sand.

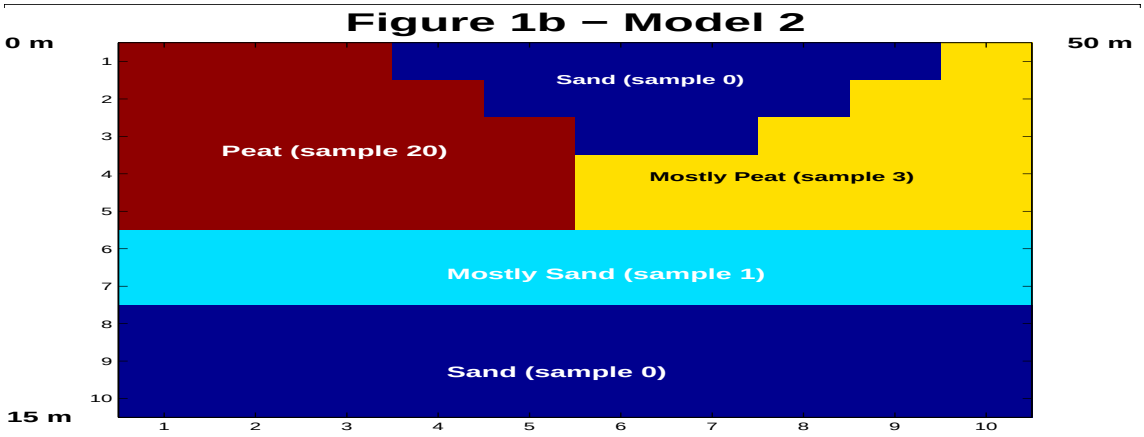


Figure 1b – Realistic Field Model 2 of Sand-Peat Soil Distributions.

Model 2 in Figure 1b is based on a site at Sherman Island in the Sacramento-San Joaquin Delta in northern California (Boulanger et al., 1998).

These soils are based on man-made soils used for laboratory measurements of ultrasonic velocities (Trombino, 1998; Berge et al., 1999; Bonner et al., 1999). Compressional (Vp) and shear (Vs) velocities were measured as functions of pressure between 0 and 15.6 psi (0 to 0.1 MPa). These soils have linear velocity gradients. (See Figures 2 and 3.)

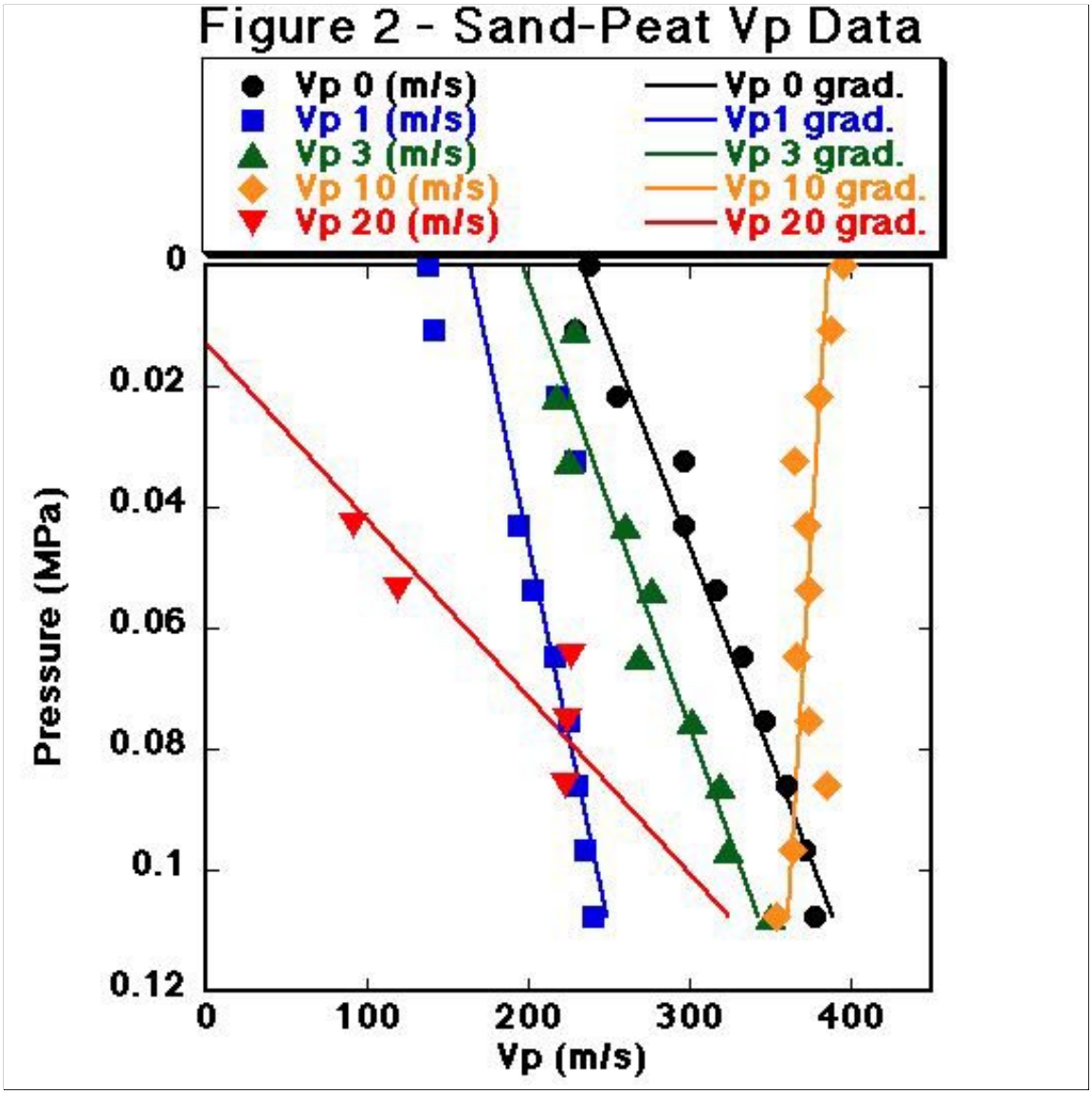


Figure 2 - Vp Laboratory Data.

Ultrasonic compressional wave velocity (Vp) data were measured at pressures between 0 and 15.6 psi (0 to 0.1 MPa). Colored solid symbols in Figure 2 represent data for the five different sand-peat mixtures whose velocities were measured in the laboratory. Colored lines indicate linear fits to the velocity data.

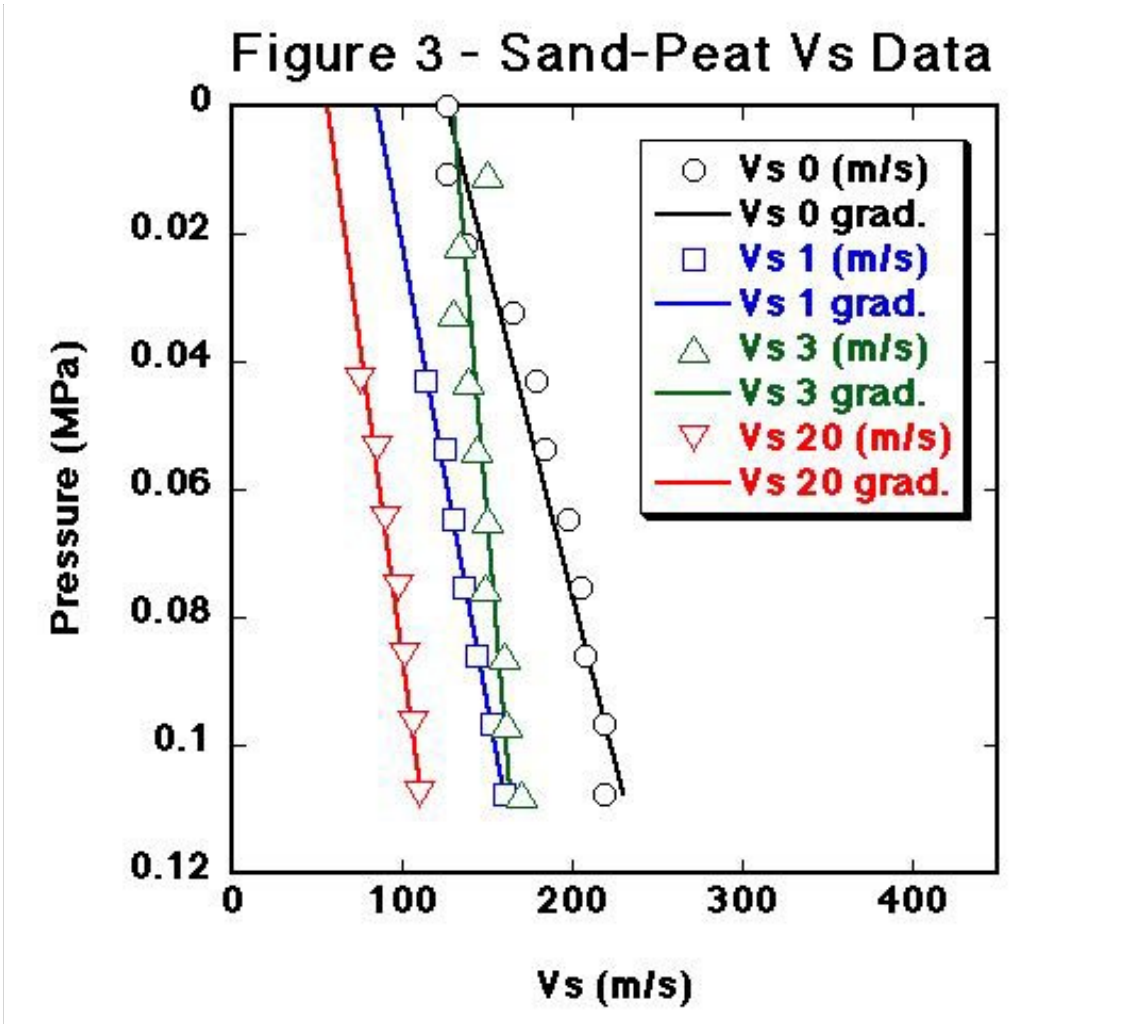


Figure 3 - Vs Laboratory Data.

Ultrasonic shear wave velocity (Vs) data presented in Figure 3 were measured for all but one of the samples used in Figure 2. Open symbols indicate data, solid lines indicate linear fits, as in Figure 2.

## Simulating Field Data from Laboratory Measurements

For Models 1 and 2, we use the linearized laboratory data (red lines in Figure 4) to simulate true seismic velocities for our forward models (Figure 5). We include noise (blue lines in Figure 4) comparable to the uncertainty in the laboratory velocity measurements to simulate the velocity distribution that would be measured in a field experiment (Figure 6).

We compare the velocity spatial distribution and heterogeneity in the simulated field data and the laboratory data for Vp (Figure 4a) and Vs (Figure 4b). The linear fits to the data in

Figures 2 and 3 were used to generate the synthetic velocity model for Figure 1a. Figure 4a shows a 1-d representation of the Vp velocity distribution over the 100 cells in the grid of Figure 1a. Cell 1 in the plot in Figure 4a refers to the upper left corner of the model, and cell velocities are plotted row by row through the model, with cell 100 referring to the lower right corner of the model.

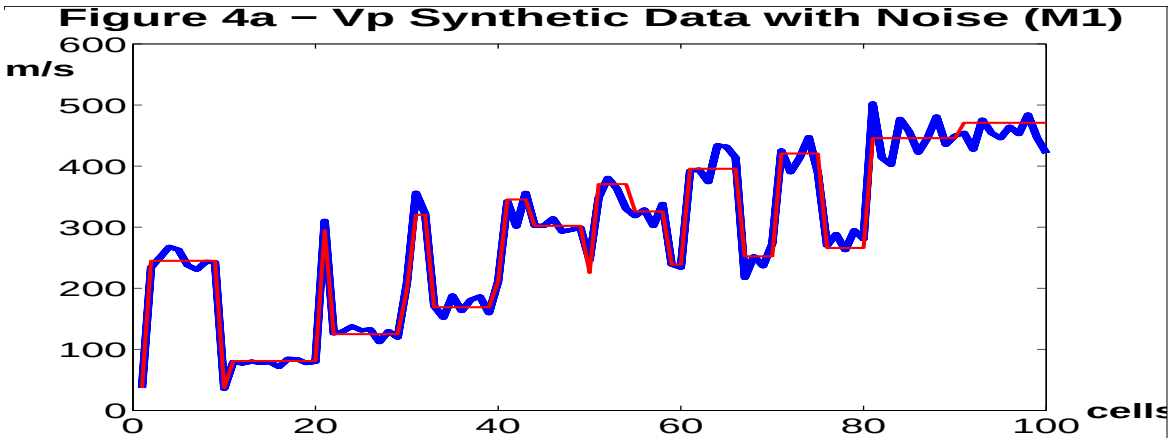


Figure 4a – Vp Synthetic Data with Noise for Model 1.

The red solid line indicates the true velocity distribution representing the model of the earth in Figure 1a. The blue line indicates noisy synthetically-generated data to be used as the field velocity observations. Figure 4b shows the shear wave velocity distribution, analogous to Figure 4a for Vp.

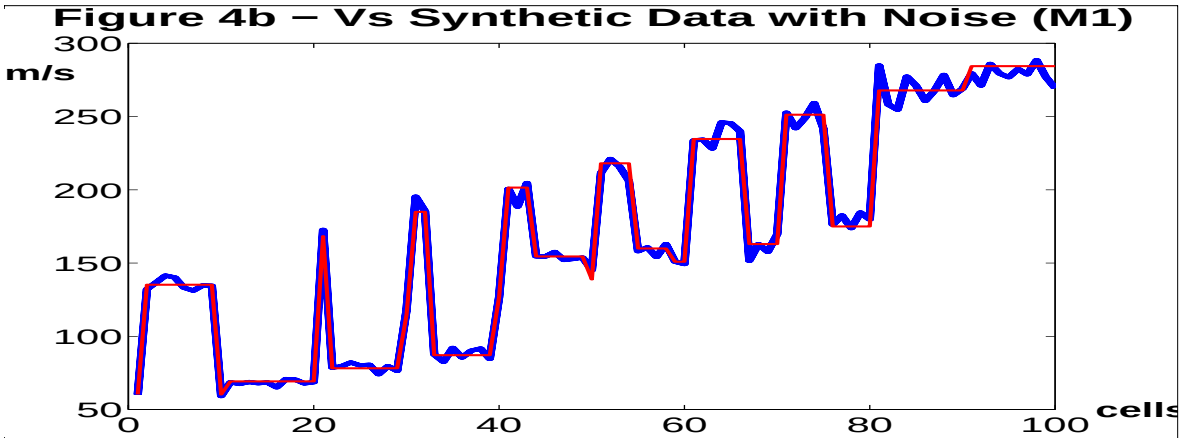


Figure 4b – Vs Synthetic Data with Noise for Model 1.

Figures 5a and 5b show the true 2-d velocity distribution for Model 1. The velocities at each grid point were calculated from the linear approximations to the experimental data in Figures 2 and 3. Figure 5a shows the true velocity distribution for Vp, and Figure 5b for Vs. These velocity distributions are also represented by the red lines in Figure 4.

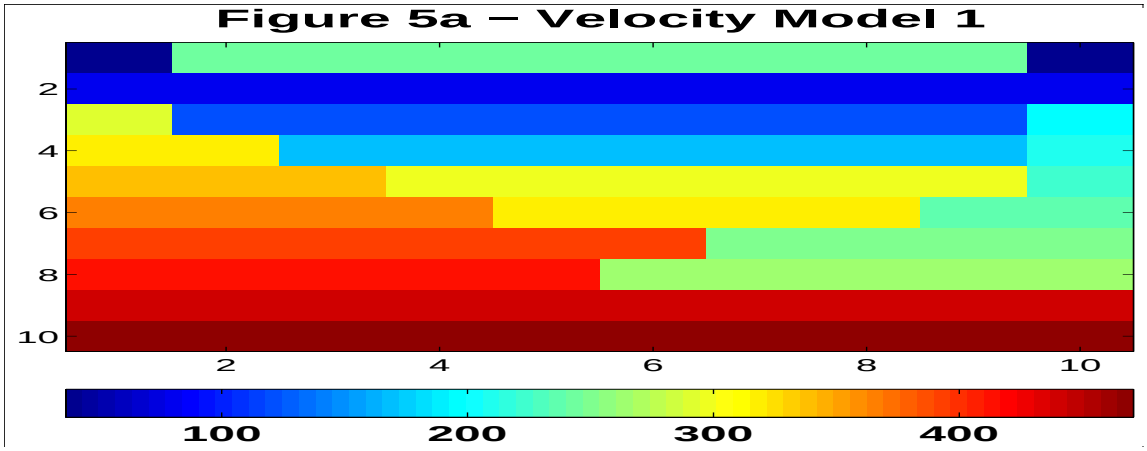


Figure 5a – Velocity Model 1.

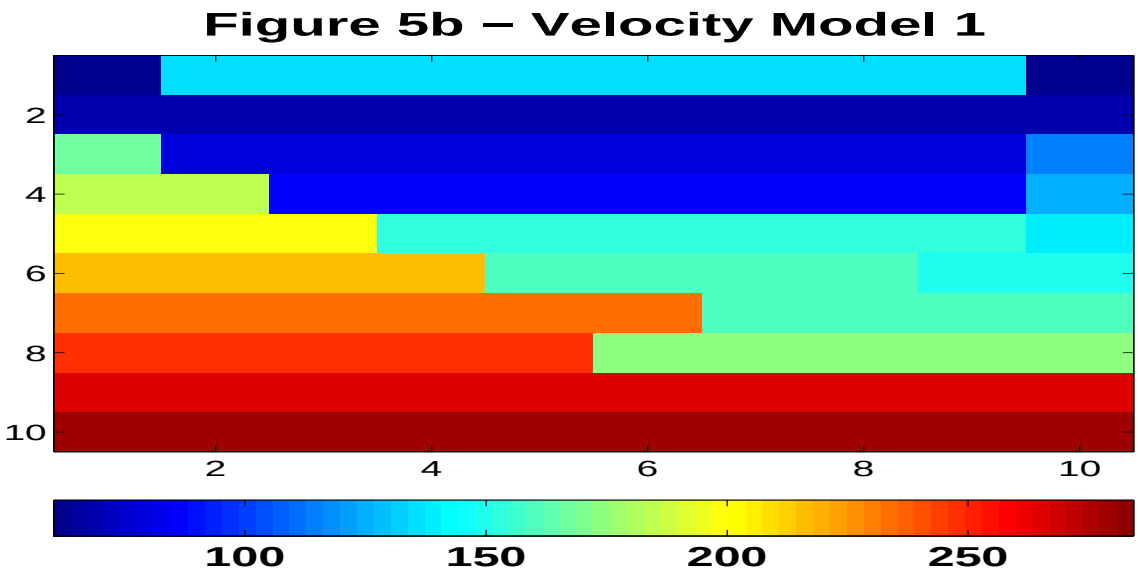


Figure 5b – Velocity Model 1.

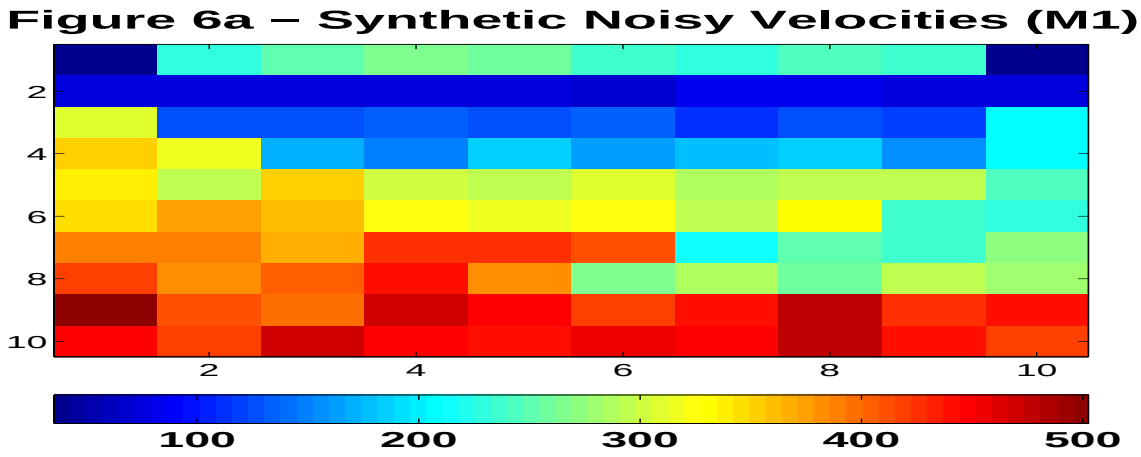


Figure 6a – Synthetic Noisy P Velocities for Model 1.

Figures 6a and 6b show the synthetic noisy velocity distribution for Model 1. The velocities at each grid point were calculated from the linear approximations to the experimental data in Figures 2 and 3, with 15% random noise added. This amount of noise is proportional to the accuracy of the laboratory measurements. Figure 6a shows the noisy velocity distribution used as field observations for Vp, and Figure 6b for Vs. These velocity distributions are also represented by the blue lines in Figure 4.

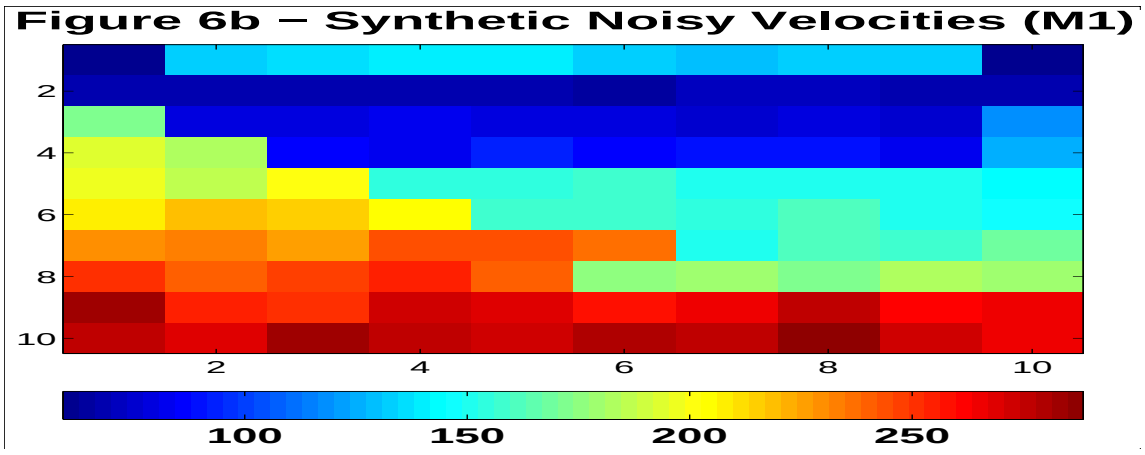


Figure 6b – Synthetic Noisy S Velocities for Model 1.

To recover the soil distribution in the shallow subsurface (Figures 1a,b) from the simulated field data (Figures 6a,b), we developed an inversion code. We built a 10x10 grid to represent the shallow subsurface. Each cell in the grid is assumed to have constant soil composition, constant density, and constant velocity. For a given point at a given depth, the code calculates the misfit between the observed seismic velocity (Figures 6a,b) and linear fits to laboratory ultrasonic velocity measurements at the appropriate pressure (Figures 2,3). The misfit in each cell in the grid is given by the L2 norm (square of the

difference of the velocities). The code repeats this procedure for the four possible soil types, for Vp and Vs, over the 100 cells. The code assigns a soil type to each cell by choosing the soil that gives the minimum misfit for the velocities. We show results to recover soil mapping for three cases: (1) constrained by using only Vp velocity distributions, (2) constrained only by Vs velocity distributions, and (3) constrained by using both Vp and Vs.

## Results and Discussion

We show how the addition of the S velocity data will constrain the inversion in realistic models when used in conjunction with the P velocities.

Features of the true models are not resolved in the same way by the Vp and Vs data because of differences in the behavior of Vp and Vs with pressure and differences in the noise distributions. Laboratory data provide the pressure (depth) dependence of velocities for different materials, as well as the velocity values at given pressures (depths) for each material. Different soils may have similar Vp values at some depths, or may have similar Vs values at some depths, leading to ambiguity in what material the reconstruction finds at those depths. For some soils the gradients may be very gradual and for others the gradients may be very steep, which affects the location of soil boundaries in the reconstruction. This dependence of various reconstruction features on Vp and Vs is shown for two specific models in this work (Figures 7a,b,d,e).

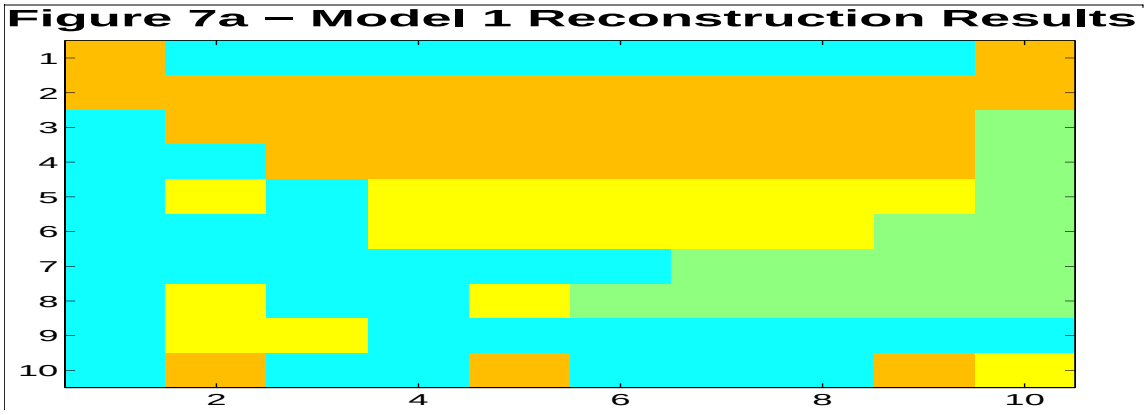


Figure 7a – Model 1 Reconstruction Results.

Figure 7a shows reconstruction results for Model 1 using Vp only. Blue indicates pure sand; green indicates a mixture of about 12% peat, 88% sand; yellow represents a mixture of about 20% peat, 80% sand; and orange represents a mixture of about 70% peat, 30% sand.

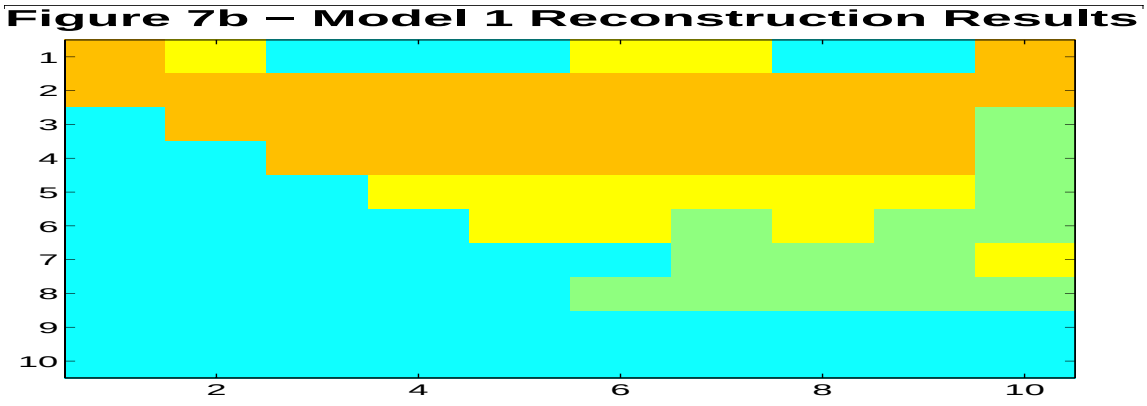


Figure 7b– Model 1 Reconstruction Results.

Figure 7b shows reconstruction results for Model 1 using Vs only.

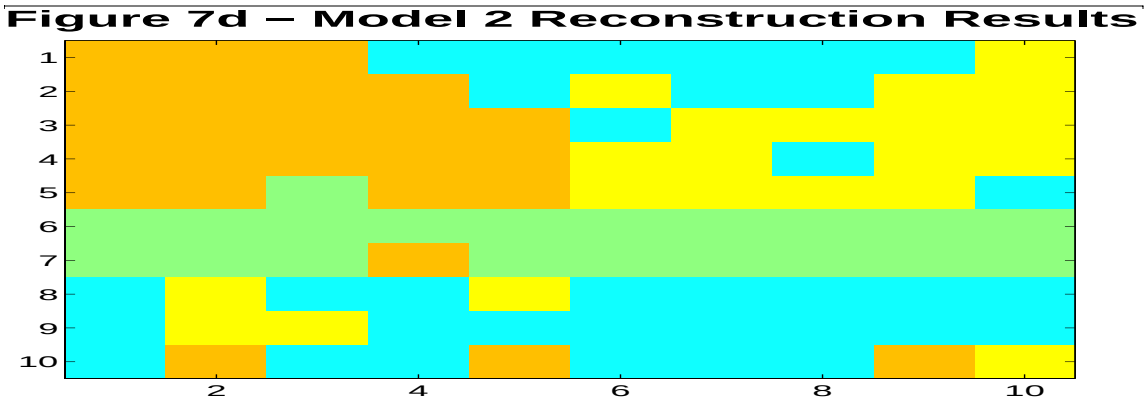


Figure 7d – Model 2 Reconstruction Results.

Figure 7d shows reconstruction results for Model 2 using Vp only.

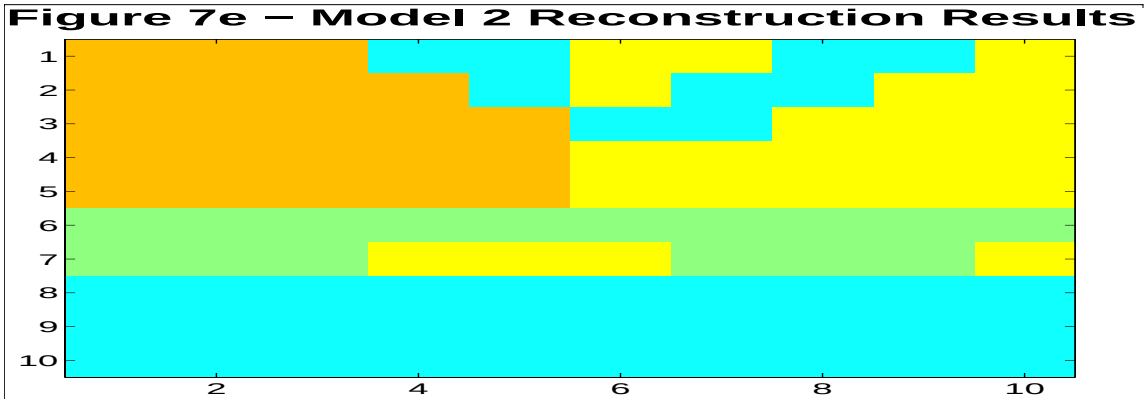


Figure 7e – Model 2 Reconstruction Results.

Figure 7e shows reconstruction results for Model 2 using Vs only.

Results obtained using both Vp and Vs may resolve features that are not resolved by either type of velocity data alone. The availability of the laboratory data for Vp and Vs at low pressures has allowed us to quantify what improvement in resolution may be possible if Vp and Vs seismic data are used together to image the shallow subsurface (Figures 7c,f).

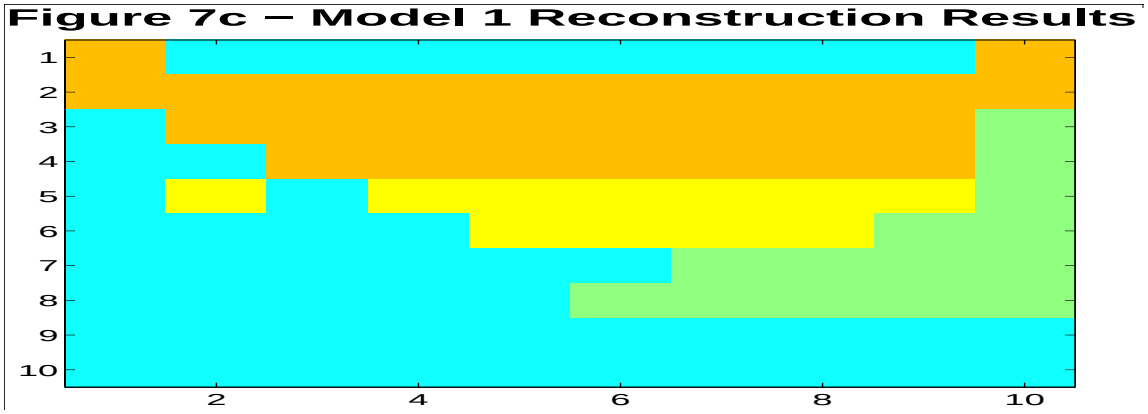


Figure 7c – Model 1 Reconstruction Results.

Figure 7c shows reconstruction results for Model 1 using both Vp and Vs.

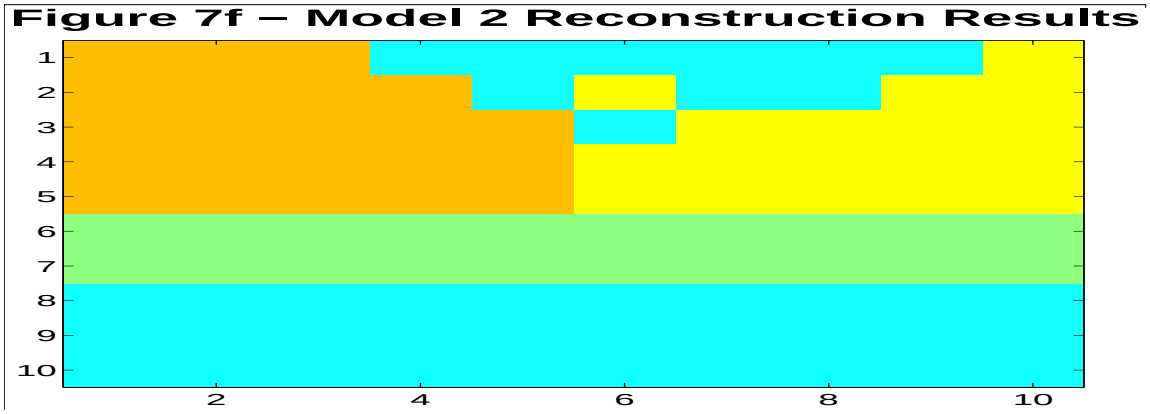


Figure 7f – Model 2 Reconstruction Results.

Figure 7f shows reconstruction results for Model 2 using both Vp and Vs. Figures 7a,b,d,e show that features of the true models (Figure 1) are not resolved in the same way by the Vp and Vs data because of differences in the behavior of Vp and Vs (e.g., Figure 4 for Model 1) with pressure and differences in the noise distributions. The results in Figures 7c and 7f show the improvement in resolution when both kinds of velocity data are available.

## Conclusions

Our results for Models 1 and 2 show the importance of having Vs as well as Vp field measurements to constrain the recovery of shallow subsurface soil distributions. In the two realistic situations that we studied, the two datasets together provided better estimates of subsurface structure than either Vp or Vs alone could provide. The reconstruction is unreliable where laboratory data are sparse. Future work will investigate other situations in which the method does not perform well. The availability of high-quality laboratory data is a key element of this approach.

The addition of further constraints such as electrical measurements would reduce this ambiguity. Future work with additional laboratory data will improve our ability to infer lithology from field data. Physical properties measurements made under controlled conditions are critical for interpreting field data in engineering and environmental studies.

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